The Pan-Pacific Planet Search: A southern hemisphere search for planets orbiting evolved massive stars

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Abstract.
The vast majority of known extrasolar planets orbit stars with a narrow range of masses (0.7-1.3 $M_\odot$). Recent years have seen rapid growth in our knowledge about the properties of planetary systems with host stars significantly more massive than the Sun. Planet formation models predict that giant planets are more common around higher-mass stars ($M_* > 1.5 M_\odot$). However, these types of stars pose severe observational challenges while on the main sequence, resulting in a strong bias against them in current planet searches. Fortunately, it is possible to obtain high-precision Doppler velocities for these massive stars as they evolve off the main sequence and cool as subgiants. We describe the Pan-Pacific Planet Search, a survey of 170 subgiant stars using the 3.9m Australian Astronomical Telescope. In collaboration with J. Johnson's Keck survey of Northern "retired A stars," we are monitoring nearly every subgiant brighter than $V = 8$. This survey will provide critical statistics on the frequency and characteristics of planetary systems formed around higher-mass stars.

Keywords: Extrasolar planetary systems
PACS: 97.82.-j

INTRODUCTION

Radial-velocity planet searches have discovered more than 500 planets orbiting nearby stars. The planets found to date span three orders of magnitude in mass, from tens of Jupiter masses down to a few Earth masses (Vogt et al. 2010, Mayor et al. 2009). The known extrasolar planets also range in orbital separation from a few stellar radii to more than 5 AU, and encompass the full range of orbital eccentricities from circular ($e = 0$) to incredibly elliptical ($e = 0.94$).

The range of host-star masses probed by current radial velocity surveys, however, remains very narrow. Most of the target stars fall in the range 0.7-1.3 $M_\odot$(Johnson 2007, Valenti & Fischer 2005). This is a consequence of the technical requirements of Doppler exoplanetary detection, which demand that stars be cool enough to present an abundance of spectral lines, and rotate slowly enough that their absorption lines are not significantly broadened by rotation. Stars of lower mass (e.g. M dwarfs) are intrinsically faint in the optical, making the acquisition of high signal-to-noise spectra extremely expensive in telescope time (Endl et al. 2006). Main sequence stars of higher mass

have few usable absorption lines (due to their high temperatures), and also tend to be fast rotators ($v\sin\ i > 50\ \mathrm{km\,s^{-1}}$; Galland et al. 2005) due to their youth. Only the most massive planets can be detected orbiting A and F dwarfs. It is only recently that a significant number of planetary systems have been discovered orbiting massive stars. These stars have proven to be a fertile hunting ground for interesting planetary systems, such as the 4:3 mean-motion resonant planets orbiting HD 200964 (Johnson et al. 2011). Now, some headway is beginning to be made in addressing the crucial question of how planet formation depends on stellar mass (e.g. Bowler et al. 2010, Johnson et al. 2010, Sato et al. 2010).

The critical role of subgiants

In the core-accretion theory of planet formation (Lissauer 1995, Pollack et al. 1996), solids in the protoplanetary disk accrete into rocky cores. When these cores reach about $10\,M_{\mathrm{earth}}$, they have sufficient gravity to rapidly accumulate disk gas and form giant planets, with final masses $M_p \gtrsim 100\,M_{\mathrm{earth}}$. A prediction of this model is that planet mass should positively correlate with host star mass, since increasing the mass of the star also increases the mass of the protoplanetary disk. Giant planets should then be more common around higher-mass stars. Observational results to date support this prediction (Johnson et al. 2010, Johnson 2007). The number statistics are poor at both the high- and low-mass ends of this trend, but suggest that high-mass stars are indeed more likely to host Jovian planets. Results from the Lick and Keck survey of evolved A stars (Johnson et al. 2010) indicate a planet occurrence rate approaching 20% for stars with $M_* > 1.5\mathrm{M}_\odot$. Further headway has been made at the low-mass end of this trend: Endl et al. (2006) derive an upper limit for the giant planet occurence rate of 1.3% in a sample of 90 M dwarfs, while Johnson et al. (2007b) derive a similar rate (1.8 ± 1.0%) from their Keck M dwarf survey which was sensitive to lower masses and longer periods.

The core-accretion model also predicts that metal-rich disks are more efficient at forming cores, due to their enhanced surface density of solids. Detailed planet-formation models by Ida & Lin (2004) predicted that metal-rich protostellar disks would be more likely to form detectable planets. Gonzalez (1999) first noted that planet-hosting stars appeared to be unusually metal-rich. The current sample of extrasolar planetary systems appears to support this prediction: Fischer & Valenti (2005) show that stars with twice solar metallicity ([Fe/H]=+0.3) are about 3 times more likely to host a planet than stars with solar metallicity.

However, the causal mechanism for this observed relationship is still not completely settled. While the core-accretion scenario does predict that metal-rich stars will preferentially form planets, an alternate "pollution" model can also explain this effect. In this scenario, planet host stars are metal-rich because debris from the planets' formation has enriched the surface layers of the star. In this case, the enhanced metallicity of the star extends only to the convective zone (Laughlin & Adams 1997). These two hypotheses can be tested by determining the planet-metallicity relationship for *subgiant* stars. When a star evolves off the main sequence, the convective zone increases in size by about a factor of 35 (Pasquini et al. 2007). If the high metallicities observed in planet hosts are

due to pollution, this expansion of the convective zone will significantly dilute the extent of that pollution, and the subgiant's photosphere would return to its "birth" metallicity. Hence, one would *not* expect a significant correlation between metallicity and planet frequency for subgiants. If the enhanced metallicity of planet hosts is primordial in origin, however, then the planet-metallicity correlation observed for dwarf stars would also hold for subgiants. Previous investigations into this issue have so far shown no evidence for the pollution scenario (Valenti & Fischer 2008). Quirrenbach et al. [24] have recently presented tentative evidence for a planet-metallicity correlation in their sample of 373 K giants.

Subgiants (i.e. high-mass stars that have just evolved off the main sequence) provide a means to address two critical questions facing exoplanetary science. First, they develop the multitude of narrow absorption lines critical for precision radial velocity work, because the photospheres of these stars expand and cool as they leave the main sequence, their rotational velocities drop. Second, their "birth" metallicity is revealed as any potential pollution effects are diluted when their convective zones expand.

We have begun a survey of Southern metal-rich ([Fe/H]$>$0.0) subgiants which will tackle both these key issues – planet frequency for "retired A stars," and planet frequency as a function of birth metallicity in the same stars. Our goal is to enlarge the growing sample of planets around massive stars to strengthen the emerging trend between stellar mass and planet occurrence. We will also investigate the planet-metallicity correlation among evolved stars in order to test pollution scenarios. Our completed survey will dominate the number statistics for exoplanetary detections around metal-rich subgiants.

THE PAN-PACIFIC PLANET SEARCH

Target Selection

This program is using the 3.9m Anglo-Australian Telescope (AAT) to observe a metal-rich sample of Southern Hemisphere subgiants. We have selected 170 Southern stars with the following criteria: $1.0 < (B-V) < 1.2$, $1.8 < M_V < 3.0$, and $V < 8.0$. By requiring $(B-V) > 1$, we extend the red limit of the Johnson et al. (2006b) survey to the colours redward of $(B-V) = 1.0$ that stellar models indicate will be dominated by metal-rich subgiants (Girardi et al. 2002). This will allow us to obtain improved planetary detection statistics at [Fe/H]$>$0.0, and also (in light of the observed positive correlation between stellar metallicity and planet occurrence) deliver a roughly equivalent number of planetary detections to that obtained at Lick and Keck (though for metal-rich hosts). At the same time, by requiring $M_V > 1.8$, we exclude giant-branch stars, which have significant intrinsic velocity noise ("jitter") due to stellar activity and pulsations (Saar et al. 1998, Wright 2005) – typically about 20 m s^{-1} (Hekker et al. 2006). Our target list includes about 30 stars from the Lick survey; this overlap will serve as a check on the systematics between the two telescopes. These 170 metal-rich stars complement the metallicity-unbiased Northern stars in the Lick & Keck survey. Together, the three telescopes are observing more than 600 stars: nearly every subgiant in the entire sky brighter than $V = 8$.

Progress to date

This program has been awarded long-term status at the AAT, with 10 guaranteed nights per semester through 2012 July. As of 2010 October, we have obtained 3-5 observations for every target, with a signal-to-noise (S/N) of 100 per pixel. Only 55% of assigned time has resulted in usable data due to unusually poor weather conditions resulting from a prolonged La Niña event in 2009-10.

As we are using the iodine-cell method to obtain precision Doppler velocities (Valenti et al. 1995, Butler et al. 1996), the spectra are superimposed with a forest of I_2 absorption lines between 5000 and 6200 Angstroms. These sharp features are used for a high-precision determination of the spectrograph point-spread function, which in turn enables us to correct for instrumental effects and obtain a precise radial velocity measurement. We will obtain Doppler velocities using the *Austral* code as first discussed in Endl et al. (2000). *Austral* is a proven Doppler code which has been used by the McDonald Observatory planet search programs for nearly 10 years (e.g. Endl et al. 2004, 2006; Wittenmyer et al. 2009).

Nearly all spectra obtained to date contain iodine lines, but we can use the iodine-free regions of these spectra to perform preliminary stellar abundance analysis. The equivalent widths (EWs) of over 200 lines from 21 elements will be measured, including three light elements (C, N, O), four α-elements (Mg, Si, Ca, Ti), three odd-Z light elements (Al, K, Sc), seven iron peak elements (Ti, V, Cr, Mn, Fe, Co, Ni), and five neutron-capture elements (Y, Ba, La, Pb, Eu). The abundances are determined by the line synthesis program ABONTEST8 by P. Magain (Liege, Belgium), based on model atmospheres interpolated by a plane-parallel, homogeneous and local thermodynamic equilibrium (LTE) model grid by Kurucz & Bell (1995). Non-LTE effects are taken into account for several elements (e.g. O, Mg, Al). Israelian et al. (2009) reported that Lithium is depleted in planet-host dwarfs, while this phenomenon still remain unclear for higher mass stars. A spectral synthesis will be performed for Li 6707 Angstroms to determine the Li abundances. Using the high resolution, high signal-to-noise spectra in this planet search program, the detailed chemical abundances, as well as basic stellar parameters of the subgiants can be obtained. It is important to understand stellar nucleosynthesis and the chemical evolution history of the Galaxy by studying these stars in post-main-sequence stage. These data will also help us to investigate different patterns of chemical abundance between subgiants with and without planets, and thus understand planet formation process around different types of stars.

ACKNOWLEDGMENTS

RW acknowledges support from a UNSW Vice-Chancellor's Fellowship. We are grateful to the AAT Time Allocation Committee for granting this program long-term status.

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